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A four-parameter model for the estimation of rainfall frequency in south-west England

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Summary

A new method for the estimation of the frequency of heavy rainfall in south-west England has given results which indicate that big storms are more frequent than previous evidence suggests. The results are consistent with probability assessments of the expected return periods. The implications of the results are described.

1. Introduction

The two most well known methods that are used to estimate the return period (i.e. the number of years within which a particular extreme value is likely to be exceeded only once) of rainstorms, namely the Bilham method (Bilham 1935) and that used in Volume II of the *Flood Studies Report* (FSR-II) (Natural Environment Research Council 1975) produce different results according to the rarity of the storm and the average annual rainfall of the site (Kelway (1977) and Marshall (1977), respectively). In general the FSR method gives the higher return periods. This difference is of great practical importance for the design of culverts, flood alleviation schemes, and reservoir spillways. In the event of the capacity of an underdesigned spillway being exceeded, the possibility of dam failure, although slight, is too great to be dismissed in view of the damage and likely loss of life. FSR-II grew out of the acknowledged inadequacies of the now largely extinct Bilham method, especially with its uniform treatment of storms irrespective of their location. However, work by Bootman and Willis (1977, 1981) showed that for parts of Somerset the FSR-II method gave an under-estimation of the magnitude of 2-day rainfall. The difference between FSR-II and the local data, especially around Bridgwater, was considered important enough for the Institution of Civil Engineers to override the general advice that local rainfall data should not be used for the estimation of floods in relation to reservoir safety in Somerset (Institution of Civil Engineers 1978). This poses the question of whether or not this problem is confined to Somerset alone.

More recent work (Folland *et al.* 1981) revised the growth factors for estimates of rainfall frequency, and the problem of the station–year method was investigated by Reed and Dales (1988), Dales and Reed (1989) and Stewart (1989) in which the number of independent stations was assessed and regional growth curves introduced. The resulting 'FORGE' method was updated in December 1989 (Stewart and Reed 1989). These studies highlight the difficulty of rainfall frequency estimation but they also beg the question of an independent test in order to assess the validity of the results. A central problem of frequency analysis is that the data are often inadequate (Tabony 1983), but the chief problem of the FSR-II and FORGE methods is that they may be based upon dependent records. In addition they are both based upon 2-day rainfall which masks the true intensity characteristics; it is likely that this database will contain several different populations of rainstorm. For example, the largest daily rainfall at Martinstown occurred over a period of 18 hours (Twort *et al.* 1985). As time progresses more unprecedented

rainstorms are reported (Acreman 1989) and they suggest that values of probable maximum precipitation are too low.

This paper reports the results of an investigation into rainfall frequency over the Somerset Division of the Wessex Water Authority and the South West Water Authority areas. The area was chosen partly because it includes the area covered by Bootman and Willis (1977) who only considered 2-day rainfall, and also because south-west England is prone to heavy rainfall (Rodda 1970).

2. Study area and methods

A total of 44 autographic rain-gauge records were used in the study. Their distribution is shown in Fig. 1, and their location, elevation, duration of record and model parameter values given in Table I.

Much of the south-west peninsula is represented with the exception of a broad band between Exeter and Barnstaple. The records were of good quality with almost 100% coverage in the years analysed. Where one month or more was missing then that year of data was discarded. A careful check on daily rainfall was made in the event of an odd day's record being lost. The annual maxima of 1-, 2-, 4-, 8-, 12-, and 24-hour rainfalls were then subjected to an extreme frequency analysis wherein the return periods were calculated using the formula proposed by Clark (1983) which was based on a comparison of the theoretical return periods, and the return generated by a Monte Carlo analysis of a perfect 10 000-year record wherein the return periods were calculated using $N + 1/M$. The resulting formula gives results which are very similar to the Gringorten formula as used in the FSR-II. The rainfall data were then plotted onto log Gumbel paper. This approach has been used by Perry and Howells (1982) and Dunne and Leopold (1978) when analysing rainfall frequency. The use of the logarithmic scale is preferred because it overcomes the problem encountered in data presented by Rodda (1970) and Tabony (1983), namely the apparent very high return periods for the highest events, herein called rank 1 events. In addition, if the data plotted on log Gumbel paper are then re-plotted onto linear Gumbel paper there are serious problems in the interpretation of the return period of the extreme events. The use of log Gumbel plotting paper gives rise to higher magnitudes of rare events which lie outside the range of the data.

The line of best fit was then fitted to the data using linear regression but omitting the largest event on account of its effect upon the result. The equation is of the form

$$\log Y = aX + b$$

where X (the reduced variate) is

$$-\ln_e\{-\ln_e(1 - \frac{1}{T})\}$$

where T is the return period in years.

It was found that at certain sites the regression lines gave impossible values for a given duration of rainfall

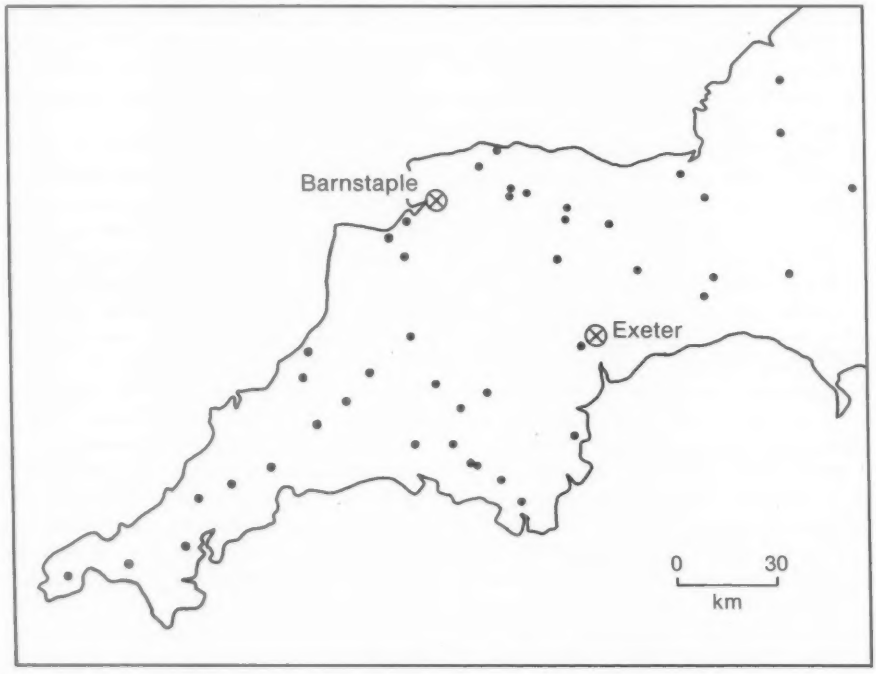

Figure 1. Distribution of autographic rain-gauge sites in south-west England used in this study.

because the value of a in the equation was not constant for all durations owing to the random nature of the data. To overcome this problem the average value of a was calculated to give, for all storm durations

$$\log Y = \bar{a}X + b.$$

This simplified the remainder of the analysis and acknowledges the fact that at higher return periods there cannot be more rain in one hour than in two. Fig. 2 shows the results of the method of analysis for two sites. From the results of the frequency analysis of 21 sites whose data were in excess of 15 years the four-parameter model was constructed.

3. The four-parameter model

For a method to predict the rainfall frequency at a site without any records it is essential that explanatory variables be identified which give realistic results. Considerable experiment revealed that four parameters

Table I. Site details and derived parameter values

Site name	National Grid Reference	Altitude (m)	Length of record (yrs)	AAR (mm)	Slope (deg.)	2-year, 24-hour rainfall (mm)	24−1 hour difference 2-year rainfall (mm)
Barrow Gurney	ST538672	91	7	883	36	44.3	32.4
Bastreet	SX244765	233	25	1706	28	59.5	45.3
Bideford	SS454271	4	11	912	35	45.4	33.4
Blackdown	SX522813	320	24	1650	28	59.1	44.9
Burrator	SX552685	221	23	1555	29	58.2	44.2
Cannington	ST245394	23	15	793	38	40.2	29.0
Carthew	SX002559	221	9	1400	30	56.4	42.7
Chard	ST319086	79	17	1060	33	50.1	35.7
Drift	SW437286	76	16	1191	32	53.1	39.9
Exeter	SX928917	27	8	820	37	41.5	30.1
Exton	SS961338	328	17	1500	29	57.6	43.7
Godolphin	SW602318	46	9	1080	33	50.6	37.8
Goosemoor	SS958354	369	6	1400	30	56.4	42.7
Hemyock	ST138129	165	24	1016	34	48.9	36.3
Higher Brockscombe	SX462950	186	11	1290	31	54.8	41.4
Hollamoor	SS443176	163	6	1137	32	51.9	38.9
Houndall	SX594592	188	9	1500	29	57.6	43.7
Kingsbridge	SX735441	34	7	1100	33	51.1	38.2
Ladock	SW892510	30	21	1115	32	51.5	38.5
Launceston	SX327839	128	24	1196	32	53.2	40.0
Lesnewth	SX130902	183	25	1400	30	56.4	42.7
Lowermoor	SX128831	267	9	1585	28	58.5	44.4
Lutton	SX588590	168	16	1500	29	57.6	43.7
Lynmouth	SS724495	12	7	1100	33	51.1	38.2
Maundown	ST065291	198	12	1100	33	51.1	38.2
Melbury	SS387202	143	11	1310	30	55.2	41.7
Modbury	SX667502	76	16	1200	32	53.3	40.0
North Brewham	ST722370	131	17	900	36	44.9	33.0
Northmoor P.S.	ST331330	8	39	695	40	34.5	24.3
Penryn Resr	SW778337	55	11	1159	32	52.4	39.3
Postbridge	SX653787	361	16	2032	26	61.6	46.9
Priddy	ST550505	268	13	1101	33	51.1	38.2
Princetown	SX586741	423	19	2136	26	62.1	47.3
Rumleigh	SX422680	23	11	1200	32	53.3	40.0
St. Neot	SX167707	223	24	1400	30	56.4	42.7
Simmonsbath	SS782394	381	6	1800	27	60.2	45.8
Stoodleigh	SS916185	245	8	1200	32	53.3	40.0
Sutton Bingham	ST556116	44	18	850	37	42.9	31.2
Thornmead	SS806382	387	5	1650	28	59.1	44.9
Threemilestone	SW780452	101	15	1100	33	51.1	38.2
Torquay	SX909637	8	15	898	36	44.9	32.9
Twist	ST290037	183	11	1050	33	49.8	37.1
Winstitchen	SS784389	369	11	1800	27	60.2	45.8
Woolhanger	SS698454	312	13	1800	27	60.2	45.8

of the frequency plots could be predicted using the average annual rainfall (AAR) for each site. The parameters are

(1) The 2-year, 24-hour rainfall.
(2) The 24 hour−1 hour difference in rainfall with a return period of 2 years.
(3) The slope of the frequency curve as measured in degrees.
(4) The percentage of the 24 hour−1 hour difference in rainfall for a given storm duration.

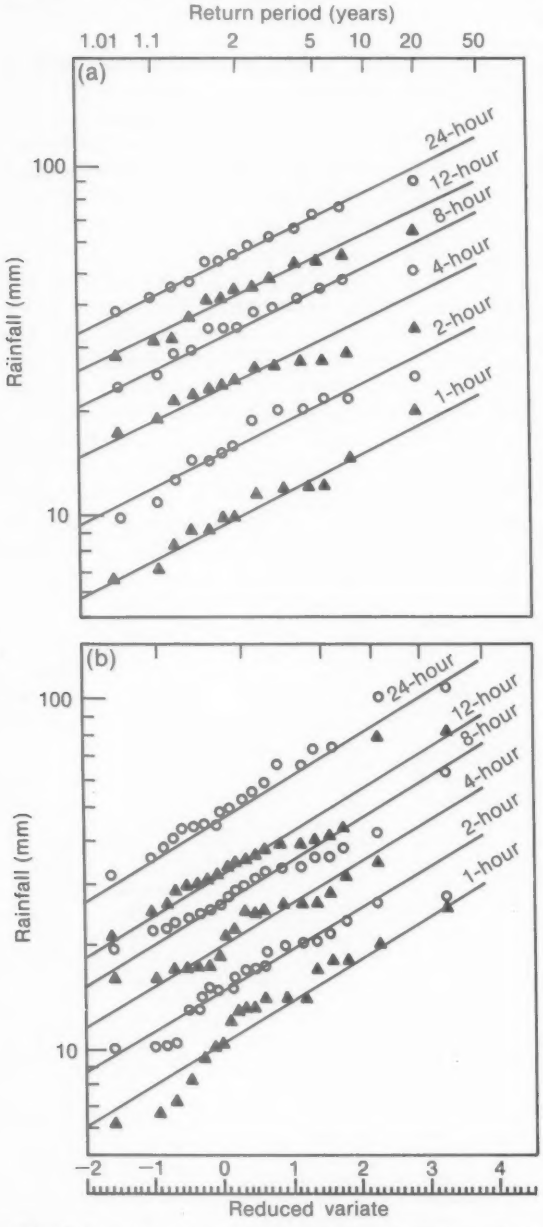

Figure 2. Rainfall frequency–duration relationships for (a) Woolhanger and (b) Hemyock.

Figs 3–6 show the results of these analyses. The AAR was extracted from rainfall records or by interpolation of the values given on the map produced by the Meteorological Office for the standard period 1941–70 for southern Britain.

The 2-year, 24-hour rainfall increases as the AAR increases, tending towards an upper limit for the wetter sites. The growth curves are very well related to the same parameter, probably on account of the drier sites being more subject to heavy downpours of convective rainfall whereas the wetter sites are more prone to relief rainfall and frontal rainfall. The 24 hour−1 hour difference in rainfall also increases with the AAR, probably because of similar reasons given above.

To predict the frequency of rainfall with other durations the stations were divided into four AAR groups, namely 690–899, 900–1099, 1100–1799 and 1800–2199 mm. The percentage of the 24 hour−1 hour difference in rainfall was calculated from the frequency plots for durations of 2, 4, 8, and 12 hours and an average percentage for each duration was obtained for each rainfall group. The results are plotted in Fig. 6 where there is a small but systematic variation between storm duration, AAR and the percentage of 24 hour−1 hour rainfall. Table II was then compiled from Fig. 6. From Fig. 5, Table III was constructed; this shows the slope of the frequency curve in relation to the growth factors for rainfall with return periods of 3–1000 years. It is not yet possible to give a reliable return period to storm events which are in excess of 100 years because of the relatively short lengths of the records. It should not be assumed that the magnitudes of a given duration of rainfall will increase indefinitely. Indeed from Jackson (1979) it appears that rainfall frequency may follow an EV2 distribution up to 10^4 years, but that beyond this an EV3 distribution is more appropriate. This means that rainfall increases at an increasing rate in relation to the return period in the range 100–10 000 years (EV2) and thereafter rainfall increases at a decreasing rate in relation to the return period (EV3). Together with the relationships in Figs 3–6, Tables II and III were used in order to predict the return periods of storms that occurred at all of the sites. The method is described in detail below.

(1) Obtain the AAR of the site from the standard-period rainfall map 1941–1970 for southern Britain, or from published records.
(2) Calculate the 2-year, 24-hour rainfall using the equation in Fig. 3.
(3) Calculate the 24 hour−1 hour difference in rainfall using the equation in Fig. 4.
(4) Calculate the 1-hour, 2-year rainfall (step (2)−step (3) above).
(5) Obtain the percentage of the 24 hour−1 hour difference in rainfall for a *T*-hour rainfall from Table II.
(6) Calculate the 2-year, *T*-hour rainfall ((percentage

of the 24 hour−1 hour rainfall difference (step (5)) × 24 hour−1 hour difference (step (3))) + 1-hour, 2-year rainfall (step (4))).

(7) Apply the equation in Fig. 5 to obtain the slope of the growth curve to the nearest whole degree.

(8) Calculate the growth factor as a ratio of storm rain in T-hour/2-year, T-hour rainfall.

(9) Interpolate from Table III the return period of the storm taking account of the non-linear progression of the return periods.

Example No. 1; Location — Launceston, AAR=1196 mm. Storm: 50 mm in 3 hours.

(1) AAR is 1196 mm.

(2) From Fig. 3 the 2-year, 24-hour rainfall is 53.2 mm.

(3) From Fig. 4 the 24 hour−1 hour difference in rainfall is 40 mm.

(4) Therefore the 1-hour, 2-year rainfall is $53.2 - 40 = 13.2$ mm.

(5) From Table II the percentage of the 24 hour−1 hour difference in rainfall for a 3-hour storm is 20.5%.

(6) Therefore the 2-year, 3-hour rainfall is $(0.205 \times 40) + 13.2 = 21.4$ mm.

(7) From Fig. 5 the slope of the rainfall growth curve is 32°.

(8) Growth factor is $50/21.4 = 2.34$.

(9) Interpolating from Table III gives a return period of 31 years.

Example No. 2; Location — North Brewham, AAR=900 mm. Storm: 40 mm in 2 hours.

(1) AAR is 900 mm.

(2) From Fig. 3 the 2-year, 24-hour rainfall is 44.9 mm.

(3) From Fig. 4 the 24 hour−1 hour difference in rainfall is 33 mm.

(4) Therefore the 1-hour, 2-year rainfall is $44.9 - 33 = 11.9$ mm.

(5) From Table II the percentage of the 24 hour−1 hour difference in rainfall for a 2-hour storm is 14.0%.

(6) Therefore the 2-year, 2-hour rainfall is $(0.14 \times 33) + 11.9 = 16.5$ mm.

(7) From Fig. 5 the slope of the rainfall growth curve is 36°.

(8) Growth factor is $40/16.5 = 2.42$.

(9) Interpolating from Table III gives a return period of 22 years.

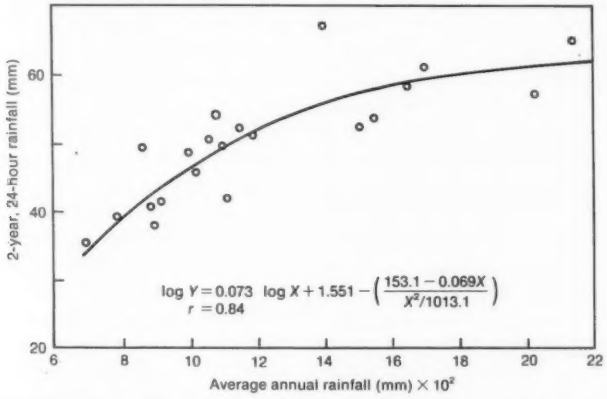

Figure 3. 2-year, 24-hour rainfall in relation to average annual rainfall.

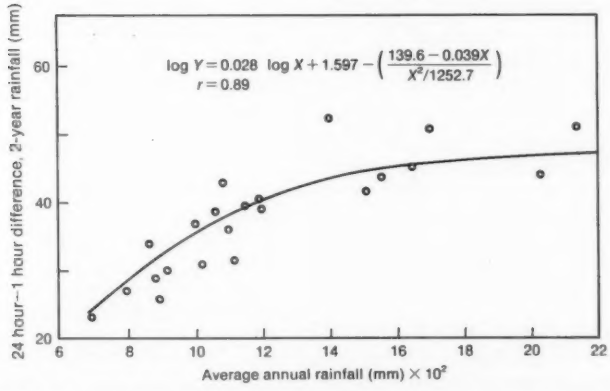

Figure 4. 24 hour−1 hour difference, 2-year rainfall in relation to average annual rainfall.

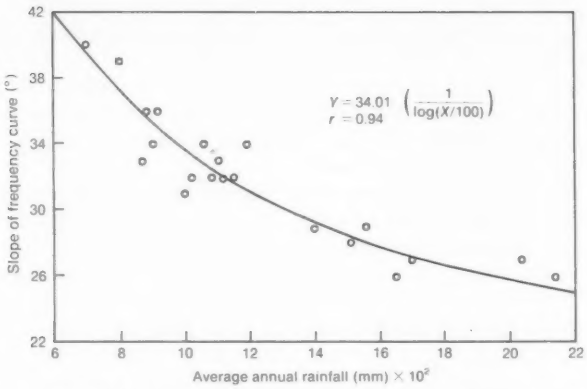

Figure 5. Relationship between the slope of the frequency curve and average annual rainfall.

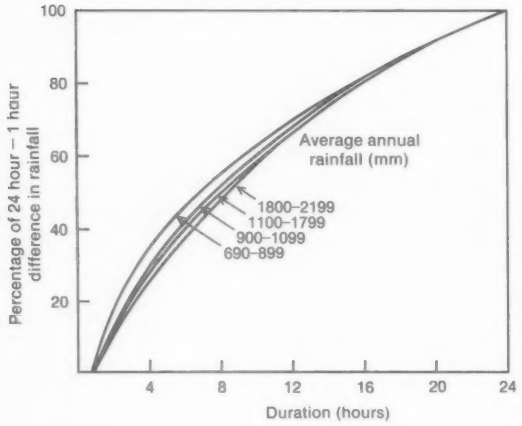

Figure 6. Relationship between storm duration, percentage of 24 hour–1 hour difference in rainfall and average annual rainfall (AAR).

4. Model testing and comparisons

To assess the validity of the results three methods of analysis were used:

Comparison with simulated return periods.

Comparison of return periods obtained using the FSR-II method.

Comparison of the return periods with those obtained from the data.

4.1 Comparison with simulated return periods

The number of sites whose return periods are in excess of the return periods which occur at the 50% and 5% probability levels was compared with the number of sites obtained by the Monte Carlo analysis described above. The largest return period was excluded from the analysis since a very rare event can occur in a short record, whereas two or more such events would be viewed as uncommon. When many more than 1 in 20 stations have storms which have return periods in excess of the return periods at the 5% probability level then there exists a prima facie case for overestimation of the return periods of the storms. Fig. 7 shows the nomogram which was used in order to assess whether the return periods are in excess of the 5% level. Table IV gives the results for the 44 sites in the study. Clearly for the FSR-II method the number of sites with return periods above the simulated periods is considerably greater than a 50–50 split; we would expect that half of the sites would have return periods above the median values and half would be below. But of even greater concern is the result that nearly half of the sites have return periods which are in excess of the 5% probability level as assessed by the FSR-II method. The distribution of these sites is shown in Fig. 8. The four-parameter model gives results which are more like what would be expected on the basis of the Monte Carlo analysis. Thus, when this evidence is considered it is difficult to give the return periods of the FSR-II very much credibility.

Table II. Percentage of 24 hour–1 hour difference, 2-year rainfall in relation to average annual rainfall (AAR) and storm duration

AAR	Storm duration											
	2	4	6	8	10	12	14	16	18	20	22	24
millimetres	*hours*											
690–899	18	34	45	54	62	69	75	81	85	90	95	100
900–1099	14	29	40	50	59	67	74	80	85	90	95	100
1100–1799	13	28	39	49	58	66	73	80	85	90	95	100
1800–2199	11	25	36	47	57	65	72	80	85	90	95	100

Table III. Growth factors for frequency curves with slopes 25–41° and return periods 3–1000 years

Slope	Return period									
	3	5	10	20	50	100	150	200	500	1000
degrees	*years*									
25	1.10	1.25	1.48	1.73	2.08	2.40	2.63	2.78	3.50	3.88
26	1.105	1.27	1.51	1.79	2.16	2.50	2.76	2.93	3.67	4.19
27	1.11	1.30	1.53	1.85	2.25	2.60	2.90	3.08	3.85	4.50
28	1.115	1.31	1.57	1.88	2.33	2.72	3.06	3.27	4.10	4.84
29	1.12	1.32	1.60	1.90	2.40	2.85	3.23	3.45	4.35	5.18
30	1.125	1.34	1.63	1.96	2.49	2.97	3.36	3.60	4.67	5.58
31	1.13	1.35	1.65	2.03	2.58	3.10	3.50	3.75	5.00	5.98
32	1.14	1.38	1.69	2.09	2.71	3.29	3.70	4.00	5.32	6.49
33	1.15	1.40	1.73	2.15	2.83	3.48	3.95	4.25	5.65	7.00
34	1.16	1.42	1.76	2.22	2.93	3.64	4.14	4.47	6.03	7.44
35	1.17	1.43	1.80	2.30	3.03	3.80	4.33	4.70	6.40	7.88
36	1.18	1.45	1.83	2.36	3.19	4.05	4.66	4.98	6.95	8.56
37	1.19	1.46	1.85	2.42	3.35	4.30	5.00	5.25	7.50	9.25
38	1.20	1.48	1.90	2.50	3.52	4.52	5.25	5.66	8.22	10.22
39	1.21	1.50	1.95	2.58	3.70	4.75	5.50	6.08	8.95	11.20
40	1.22	1.53	2.00	2.69	3.85	5.00	5.89	6.54	9.60	12.11
41	1.23	1.55	2.06	2.80	4.00	5.25	6.28	7.00	10.25	13.03

Table IV. Observed and expected frequencies of the 44 sites whose return periods are at a given probability level (p)

	FSR-II	Four-parameter model	Ideal
$p < 0.50$	30	20	22
$p \geqslant 0.50$	14	24	22
$p < 0.05$	19	2	2

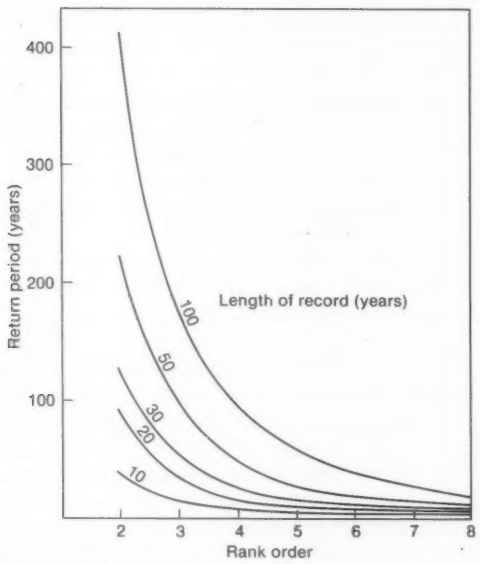

Figure 7. Relationship between rank order, return period and length of record at the $p = 0.05$ level.

4.2 Comparison of return periods obtained using the FSR-II method

The results of the two methods are compared in Fig. 9 wherein only independent storm events have been plotted. With the exception of four storm events, all remaining return periods as given by the FSR-II method are in excess of the current method. Of the remaining 29 events, 25 had return periods equal to or in excess of twice the return periods of the current method. Since FSR-II was published a revised set of growth factors has been published (Folland *et al.* 1981), although the changes are only of minor consequence.

For Launceston the return periods of seven big storms as calculated using the present method, FSR-II, and the Bilham method are shown in Table V. For the rarer events there is a larger difference between the results than for the more common storms. The reason for these differences is unlikely to be the method of data analysis, namely the plotting of the logarithm of the rainfall against the reduced variate, since out of a total of 61 events there were only 10 return periods in excess of 40 years, which is within the normally accepted limit of twice the length of record from which estimates of the return period can be made. It is much more likely that since the FSR-II method was based on the station–year approach of combining records and assuming independence then the resulting return periods are inflated if the independence assumption is invalid. Thus if 10 stations each have 20 years of records then the return period of the largest event will be 286 years with an occurrence probability of 0.50. However, independence of the records was never assessed and given the areal coverage of many big storms many rain-gauges cannot be

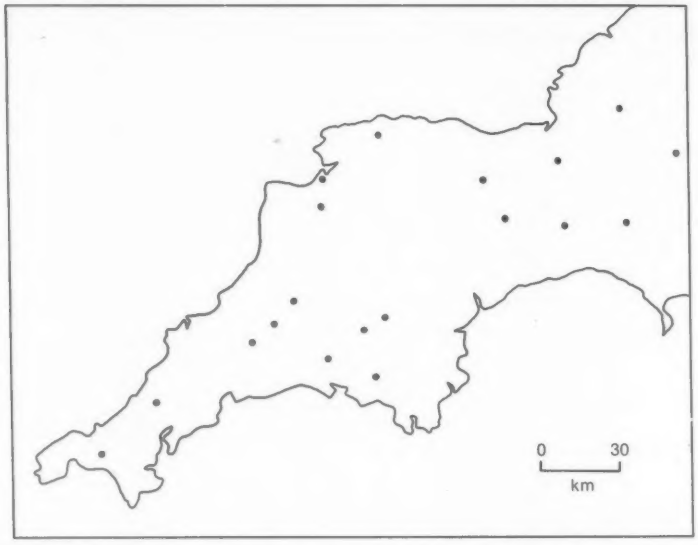

Figure 8. Distribution of sites whose return periods are in excess of the $p = 0.05$ level as assessed by the FSR-II method.

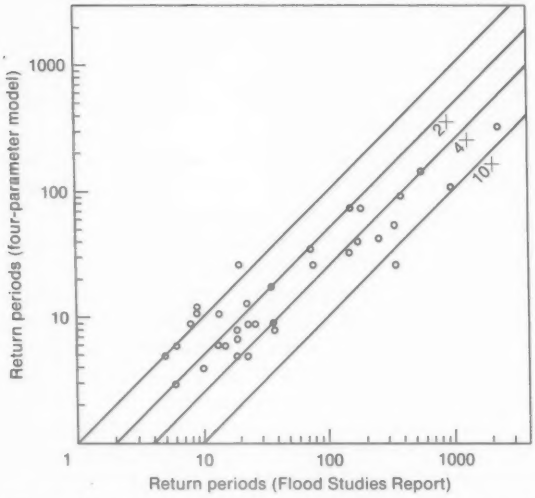

Figure 9. Comparison of the return periods using the FSR-II method and the four-parameter model.

independent of each other. The present method is based on a station by station analysis of the records, and the resulting model takes into account the variation of rainfall via the mean annual rainfall at each site. Recently May and Hitch (1989) have identified an 11-year cycle in the annual maximum 1-hour rainfall over the United Kingdom, and the possibility may exist that the records used in the present study have in some way been biased towards these periodic variations in heavy rainfall. When the dates of the records were compared with the dates of the rainfall peaks, no bias in this respect was found.

The problem of the station–year method was investigated by Dales and Reed (1989) and they described a method to calculate the number of independent sites within a given region. When this is applied to the 44 sites over south-west England only 13 were found to be independent, but some storm events can cover a big enough area to affect most if not all of these sites. An example of this is shown in Fig. 10 for 28 July 1969. Other storms have been known to cover very large areas so it is not yet possible to modify the station–year method to obtain truly independent rain-gauge sites. Furthermore, when the resulting FORGE method is applied to storm events the results which are obtained give cause for concern, see Table VI. Although some of the return periods are lower than those obtained using the FSR-II method there are some notable increases, which are for two extreme events. If the FSR-II results are at odds with both the Bilham and the present method, and a large proportion of the sites have return periods in excess of the expected return periods at the 5% level, then the results obtained using the FORGE method cannot give the user much confidence.

4.3 Comparison of the return periods with those obtained from the data

In order to investigate the reliability of the model further, the calculated return periods of storm events were compared with those derived from a direct analysis of the records. Fig. 11 shows the results wherein, with the exception of three events, all the calculated return periods are within twice the observed return periods. There is no clear evidence of a decrease in accuracy with increasing return period and only seven data points lie outside $\pm$ 1.5 times the observed values. It is impossible to state categorically if the differences are due to random variations within the data or are caused by a defect in the model.

Given the inherent uncertainty in any study of this nature the model appears to have given results which

Table V. Comparisons of the return periods, using four methods, for the seven most severe storms at Launceston

Date	Amount	Duration	Return period			
			FSR-II	Bilham	Four-parameter model	Log Gumbel plot
	millimetres	*hours*	*years*			
28 July 1969	96.5	8.9	335	113	56	42
26 Dec. 1979	95.0	18.4	150	52	19	15
15 Nov. 1963	50.8	2.8	150	38	37	42
7 July 1975	37.0	1.8	50	21	21	36
14 Oct. 1976	70.0	24.0	18	14	5	4
14 Oct. 1983	50.0	9.6	14	11	5	6
20 Sept. 1980	50.0	9.9	13	11	5	6

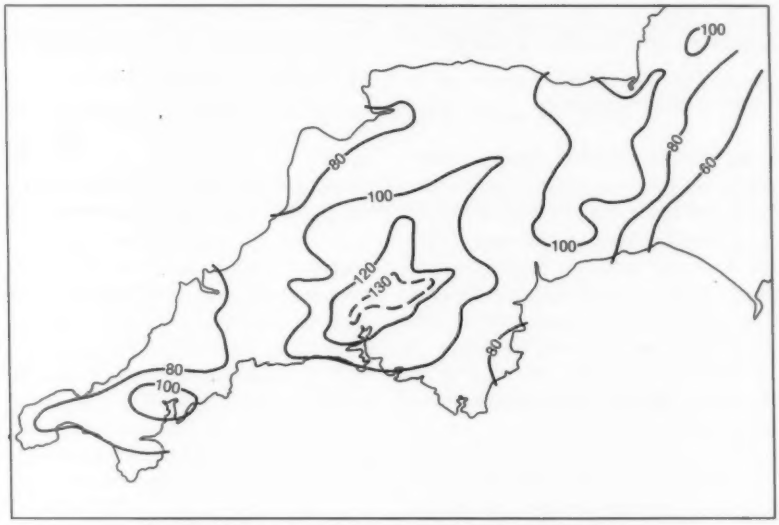

Figure 10. Distribution of 24-hour rainfall (mm), 28 July 1969.

match those from a Monte Carlo analysis of the return periods of a perfect 10 000-year record. Furthermore, an error of 50% on the return period for the 4-hour, 50-year storm for Exton gives an error in the depth of rainfall of + 4 mm or − 10 mm. The errors will be greater where the slope of the log Gumbel analysis is large. For example, for Cannington the corresponding errors are + 12 mm or − 15 mm and are equivalent to errors of + 15% and − 19% in the depth of rainfall.

5. Implications of the study

It would simplistic to extrapolate the results of the Gumbel analysis to high return periods (Reed and Stewart 1989), although Loukola *et al.* (1985) have followed this approach. But if extrapolations are made then the results are disquieting. For example, at Maundown in Somerset the 400-year, 24-hour storm is 254 mm, leaving scope for even bigger falls. Such an estimate of extreme rainfall is not unrealistic when the recorded falls during the August 1960 and June 1917 storms are considered. On this basis a fall in excess of 11 inches (279 mm) recorded at Martinstown would appear possible. Indeed Twort *et al.* (1985) quote an unofficial fall of 14 inches or 356 mm during the same event. Such falls make the estimate of the 10 000-year, 1-day fall for Wimbleball — 7 km to the west of Maundown — of 264 mm, seem modest. This estimate

Table VI. Return period of storm events using the FSR-II and FORGE methods

Date	Site	Return period	
		FSR-II	FORGE
		years	
24 Sept. 1976	St. Neot	398	240
11 July 1968	Northmoor P.S.	970	1590
12 July 1982	North Brewham	560	1000
5 Oct. 1977	Penryn Resr	266	120
28 July 1969	Launceston	335	290

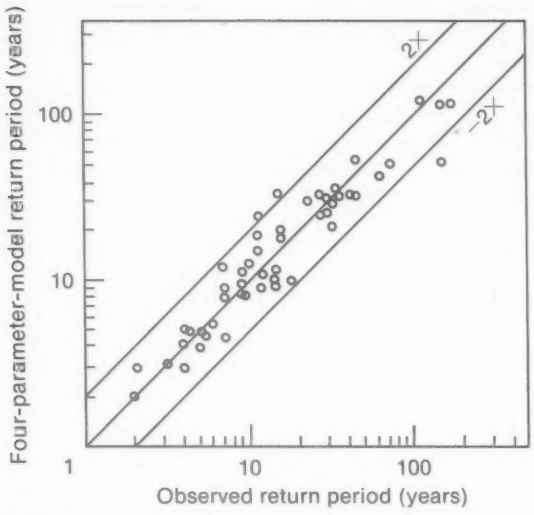

Figure 11. Comparison of the observed return periods and the calculated values using the four-parameter model.

was produced by the FORGE method (Stewart 1989). When the magnitude of a 4-hour duration storm with a return period of 2000 years is estimated using the present method, a figure around 200 mm is suggested. This is within the range of maximum recorded British rainfalls (Twort *et al.* 1985). For the Wimbleball dam site such a storm is likely to be in excess of the response time of the catchment area of 29 km^2, and assuming 100% run-off gives a peak flow of 403 $m^3 s^{-1}$, which is 100 $m^3 s^{-1}$ in excess of the design flood and the probable maximum flood quoted by Shaw (1989).

When the design of a reservoir spillway is considered, safety is of paramount importance. Records of rainfall intensity are important sources of data for design purposes. At present their biggest drawback is their very short duration. Therefore more work needs to be undertaken in order to extend the existing analysis by identifying stations which are completely independent of each other. It is likely that the widely spaced rain-gauges whose records Bilham analysed were far enough apart to be independent, so it is not surprising that the return periods which his method gives are often considerably below those given by the FSR-II method. Given that Bilham chose sites whose AAR was often below 800 mm and that there was only one gauge in south-west England, and considering that many of the sites were located near the coast, it is rather unlikely that this geographical coverage can represent the range of conditions which exist in the peninsula. In spite of this there is a closer agreement with the results using the present method and the Bilham method than with the FSR-II method.

6. Conclusions

A new method for estimating the frequency of heavy rainfall over south-west England has given results which suggest that heavy rainfall events are much more common than has been hitherto believed. By comparing the number of sites whose return periods are in excess of the 5% probability level of exceedance it is suggested that the large number of rare events as given by the FSR-II is too high. The main reason for the high return periods appears to be the pooling of rainfall data from stations that are not independent of each other. The associated FORGE method (Stewart 1989) also gives results which suggest that the problem of dependence between widely spaced rain-gauges has not yet been overcome.

A comparison of the calculated and observed return periods of storm events showed that the model was capable of giving realistic results and with an accuracy good enough to be used for design purposes.

The results which have been presented are only applicable to south-west England. It may be that the relationships here described will have to be modified for other areas. The study area covers part of the West Country and south-west England as defined by Reed and Stewart (1989); these have markedly different growth curves. Clearly for a catchment area which covers more than one region there will be problems assigning the return period of storm events. Furthermore, there can be marked intra-regional variation of the observed growth factors as this study has shown. The present method overcomes these problems by assigning a growth factor specific for the site in question in contrast to the uniform national growth-curve for the FSR-II and regional curves for the FORGE method. At present it is not possible to specify the magnitude and duration of storms in excess of the 100-year return period. This remains an important problem to be overcome.

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A verification method for aerodrome forecasts

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Summary

A new method of verifying aerodrome forecasts, either manually or by means of a computer, is presented.

1. Introduction

By verification we mean the process of comparing the actual weather of a place at a certain time with the predicted weather for the same place and time. The result of this comparison is the forecast assessment expressed as a mark out of ten.

The basic aims of the verification are (Mason 1980):

(a) the everyday checking of weather forecasts,
(b) comparing improvements after the introduction of new means and methods of weather forecasting, and
(c) testing the ability of weather forecasters.

Everyday assessment of the quality of weather forecasts can result in: taking necessary measures for the forecasts' improvement when necessary, financial determination of the forecasts' value, and improving the weather forecaster's skill.

Published papers on aerodrome forecast (TAF) verification are very sparse. Wright (1971) describes a scheme which verifies a TAF or a set of TAFs at a particular moment of the TAF's time-period. The assessment is confined to visibility, surface wind, and low cloud. Thus, strictly, the accuracy of the whole forecast contained in the TAF is not tested; it is assessed in the way that it is often used by someone requiring a knowledge of the weather at specific times for planning purposes.

Von Bezold (1969) introduced a method of verifying all the details of a TAF for a continuous period including the qualifying statements TEMPO, INTER and PROB. Wright (1971) referred to another method introduced by Hoppestad which verifies TAFs in a similar manner to Von Bezold's method but deals with probability forecasts by testing the accuracy of TAFs over long time-periods, such as 3 months. Thus, the final scores cannot be attached to individual TAFs.

This paper introduces a method that can be applied manually or by means of a computer and does more than the above methods do. It deals individually with all weather elements contained in a TAF, tests them over the whole time period, and scores each separately.

To devise this method we considered various papers that dealt with local or regional forecast verifications (Bleeker 1946, Muller 1944, Dobryshman 1972, Johnson 1969, Zverev 1972, and Murphy 1985) and the Daan's (1985) technical memorandum that introduced an objective method, carried out by a computer, for the assessment of local weather forecasts.

2. Description of the method

2.1 General

TAF assessment can be carried in real or non-real time. If a system is designed to receive TAFs and

METARs (reports of actual weather) from the telecommunication network and can decode them using suitable programs, the TAFs can be assessed at the moment of each TAF's expiry. Thus, a quick evaluation of each TAF is provided quickly which can contribute to the improvement of the following TAF (this process requires computer time in the everyday operational routine which is not normally available at aerodrome forecasting offices).

2.2 Scoring method

TAFs serve aviation purposes (World Meteorological Organization 1988) and from this point of view the most important meteorological elements are visibility, low cloud (base ≦ 5000 ft), wind (direction and speed) and weather, so all these elements must be assessed separately; the weighted average of their derived scores being the final score for the TAF. The weight coefficients which, in the same time, show the order of the importance of each element are: visibility 6, height of low clouds 5, amount of low clouds 4, wind direction 3, wind speed 2, and weather 1.

It must be mentioned here that these processes may have to be repeated two, three or even more times for the same TAF since a TAF may contain many changes. For such a TAF the final score is the weighted average of the component element scores of the TAF, where the corresponding length of time is taken as the weight for every score. Marks for the separate and total scores are in the range 0 to 10.

2.2.1 Score assessment of the meteorological elements of specific time intervals

To assess the score of a meteorological element contained in a TAF we introduce the non-linear relationship:

$$S = 10^{(M-A)/M} \qquad (1)$$

where S is the forecast assessment, A the absolute error defined as $A = |X_{\text{forecast}} - \bar{X}_{\text{observed}}|$ where X is the element under consideration. The mean value of X is calculated from the corresponding METARs; M is the maximum tolerated absolute error which adopts a score, that is,

if $A \leqq M$ then $S = 10^{(M-A)/M}$, where S is in the range 1 to 10
if $A > M$ then $S = 0$
if $A = 0$ then $S = 10$.

M depends on the operational desirable accuracy of forecasts of each meteorological element contained in TAFs, so we defined the various maximum tolerated errors following the suggestions contained in the *Manual of aeronautical meteorological practice* (International Civil Aviation Organization 1985). These are:

Visibility: 200 m up to 700 m and ± 30% between 700 m and 10 km,
low-cloud amount: 2 oktas,
low-cloud height: 100 ft up to 400 ft and ± 30% between 400 ft and 5000 ft,
wind direction: 30°, and
wind speed: 5 kn up to 25 kn and ± 20% above 25 kn.

To assess the score of the forecast weather we classified it into seven categories. Each category includes several similar weather kinds the number of which being the maximum tolerated error for the category. The indicated order within each category is considered as the value for each kind of weather, and is used for the assessment of A and hence the score S of the forecast weather. If the forecast and observed weather do not appear in the same category then $S = 0$, if they contain no weather then $S = 10$.

The various categories are:

Fog
1. fog
2. shallow fog
3. fog patches
4. freezing fog
5. mist
6 haze
7. smoke

Drizzle
1. drizzle
2. heavy drizzle
3. freezing drizzle
4. heavy freezing drizzle

Rain
1. rain
2. heavy rain
3. showers
4. heavy showers
5. rain and snow
6. thunderstorm
7. squall
8. snow
9. heavy snow

Snow
1. snow
2. heavy snow
3. rain and snow
4. rain
5. heavy rain
6. showers
7. heavy showers
8. thunderstorm
9. squall

Showers
1. showers
2. heavy showers
3. thunderstorm
4. squall
5. rain
6. heavy rain
7. snow and rain
8. snow
9. heavy rain

Thunderstorms
1. thunderstorm
2. squall
3. heavy shower
4. shower
5. heavy rain
6. rain
7. rain and snow
8. snow
9. heavy snow

Squalls
1. squall
2. thunderstorm
3. heavy shower
4. shower
5. heavy rain
6. rain
7. rain and snow
8. snow
9. heavy snow

2.2.2 Average values of the meteorological elements obtained from METARs

During each TAF validity period there is always a number of METARs, the number fluctuating according to the specific station. From here on all the METARs that fall into the duration of a TAF are called METARs of interest (MOI).

The average of all the values of an element from the MOI is the observed value of the element that is compared with that predicted in the TAF. The score for the particular element is found via equation (1). There are differences in the calculation of the average according to the method followed (manually or by computer) and according to the type of element (scalar or vector).

(a) Wind direction. The wind direction in a particular period is calculated by vector addition. Manually, addition is done graphically (e.g. by the use of a hodograph); using this process the mean vector speed and direction are both calculated. By computer the vector representing the wind is resolved into two components u and v (Brooks and Carruthers 1953) with the help of the relations

$$u = FF\sin(DD + 180)$$
$$v = FF\cos(DD + 180)$$

where u has a direction west–east adopting a negative value when it is easterly, v has a direction south–north adopting a negative value when it is northerly; DD is the wind direction in degrees and FF wind speed in knots. $\overline{\Sigma u}$ and $\overline{\Sigma v}$ are calculated from which the mean vector wind speed $\{(\overline{\Sigma u})^2 + (\overline{\Sigma v})^2\}^{1/2}$ derives. From the relation $w = \arctan |\Sigma u / \Sigma v|$ an angle $w < 90°$ is found, and by examining the signs of Σu and Σv the direction of the resultant wind is determined.

(b) Wind speed. To calculate the mean wind speed, the speed of the winds with certain directions and the speed of the variable winds are added and the total is divided by the number of METARs that include a wind observation. The ratio of the mean vector speed to the mean speed, multiplied by 100, is said to be the 'wind constancy' (Brooks and Carruthers 1953). Note that when in the TAF the term VRB (variable) has been given as the predicted wind direction, the score for the direction will be 10 if the mean wind speed derived from the corresponding METARs is less than 10 kn — otherwise the direction scores zero. The score for wind speed is calculated no matter what the predicted or observed direction was.

(c) Visibility. The mean visibility value is calculated by a weighted average of the visibility values in the MOI. Where the term CAVOK is used the visibility is taken as 9999 m.

(d) Weather. The kinds of weather that usually appear in a TAF have already been classified into seven numbered categories. To obtain the prevailing weather in a certain period of time from the METARs the following method is used. When in a particular period only one kind of the weather stated above was observed and in only one METAR, then the average weather for the complete period will be that kind of weather. When there is none of the aforementioned weather in any METAR then the weather characterization will be no weather.

(e) Amount of low cloud. To calculate the mean cloudiness that corresponds to a certain period of time, the amount of low cloud corresponding to each MOI is first determined. This amount is equal to the total of all reported low cloud in the METAR, 8/8 being taken when the total exceeds it. The mean cloudiness is then taken as the average of the MOI.

Example: METAR cloud reports for a 2-hour period from 10 to 12 UTC

Time	Cloud		
1020	2CU030	4SC035	5AC090
1050	2CB025	4CU025	4SC030
1120	2ST010	4CU030	4SC035
1150	3CU030	6AC090	

The amounts of the low cloud corresponding to the above METARs are 6/8, 8/8, 8/8 and 3/8, respectively. The mean cloudiness for the 2 hours is

$$\frac{6+8+8+3}{4} \approx 6 \text{ oktas.}$$

(f) Height of the base of low cloud. To calculate the mean height of the low cloud that corresponds to a certain period of time, weighted mean values are used. For each MOI the mean height is determined by adding the products of the height of every group of low cloud by the corresponding amount and dividing this sum of products by the total of the amount of low cloud. Then, using a similar method, the mean height of the low cloud is found.

Example: From the cloud information contained in the previous example the mean height of the low cloud for the first METAR is

$$\frac{(2\times3000)+(4\times3500)}{6} \approx 3300 \text{ ft}$$

where 2 and 4 are the amounts of low cloud (oktas) in the METAR with heights 3000 ft and 3500 ft respectively. In the same way we find that in the second METAR the mean is

$$\frac{(2\times2500)+(4\times2500)+(4\times3000)}{10} = 2700 \text{ ft.}$$

Likewise, the mean height of low cloud for the 3rd and 4th METARs is found to be 2800 and 3000 ft, respectively. The mean height, which approximately corresponds to the period of 2 hours, is found to be

$$\frac{(6\times3300)+(8\times2700)+(8\times2800)+(3\times3000)}{25} \approx 2900 \text{ ft}$$

where the divisor is the total of the four amounts of mean cloudiness.

2.2.3 TAFs with change groups (GRADU, TEMPO, INTER, PROB)

If there are change groups in the TAF then it is divided by the duration in hours of each section into time periods, and a score is found for each section, the products of the score by the duration in hours of each section being added and the total divided by 9 (for 9-hour TAFs) to find the final score.

(a) GRADU alteration. When GRADU is used, the TAF is divided into sections and the time corresponding to the half of the duration period that follows the GRADU term is taken as a separation point of every section.

Example: TAF LGAT 0110 35010 CAVOK GRADU 0204 VRB03 5000 10BR GRADU 0608 36020 9999 2CU030.

This TAF is divided into the following three sections
LGAT 0103 35010 CAVOK
LGAT 0307 VRB03 5000 10BR
LGAT 0710 36020 9999 2CU030
with corresponding durations of 2, 4 and 3 hours.

(b) TEMPO or INTER alterations. In this case the part score of the TAF corresponding to the period covered by this alteration is found separately. If, additionally, there is a GRADU group within the TAF, then the TAF is divided as described above and the score for each section found.

(c) PROB alterations. Since the prediction is given with probability the score is reckoned normally and then reduced by a percentage equal to the probability.

2.2.4 Final assessment

The final assessment is calculated from the scores of the separate sections 'weighted' for the corresponding period of time in which they are referred to, that is, every score is multiplied by the corresponding duration and all the products are added. The total divided by 9 (for a 9-hour TAF) gives the final score.

We must underline here that the final score of each section of the TAF is the weighted average score (S) obtained via equation (1) of each meteorological element described in section 2.2.

3. Worked examples

Consider the following TAF

TAF LGAT 1019 25010 9999 3CU035 5AC090 TEMPO 1113 5000 95TS 2CB020 5CU035 GRADU 1618 36012 9999 3CU035.

This TAF is first divided into two time periods (10–17 and 17–19) to take account of the GRADU group. For the period 10–17 the TEMPO section is accounted for by a further subdivision into sections of 2 hours (11–13) and the remaining 5 hours. This leads to:

first section (duration 5 hours) — LGAT 25010 9999 3CU035 5AC090,
second section (duration 2 hours) — LGAT 25010 5000 95TS 2CB020 5CU035,
third section (duration 3 hours) — LGAT 36012 9999 3CU035.

To assess this TAF we find the average values of the elements (visibility, cloud amount, wind and weather) from the MOI. Supposing that for each of the above sections of the TAF the mean values of the elements concerned have been assessed and the mean actual weather conditions are:

for the first section — LGAT 18015 9999 2CU035,
for the second section — LGAT 22015 5000 62RA 5CU030 8AS080, and
for the third section — LGAT 28015 9999 3CU035 6AC100.

One by one the elements of the TAF and the mean observed weather are compared as described in section 2.2.1; the scores of these separate elements are found in Table I. The mean general weighted score for the first section is 6.41, for the second section 5.80 and for the third section 7.86. The final score is found by reckoning weighted mean value (the weights will be the durations of the sections). Thus the final score is

$$\frac{(5\times6.41)+(2\times5.80)+(2\times7.86)}{9} = 6.59$$

giving the TAF characterization 'good' from Table II.

Table I. Scores of separate elements found in the various sections of the TAF worked example

Element weight	Elements	1st	2nd	3rd
6	Visibility	10	10	10
5	Height of low cloud	10	10	10
4	Amount of low cloud	3.16	1	10
3	Wind direction	0	1	0
2	Wind speed	1	1	2.51
1	Weather	10	2.78	10

4. Concluding remarks

The method of scoring the accuracy of the aerodrome weather predictions explained above can be a measure of their evaluation. The method may be applied for all TAFs but especially for those with a 9-hour duration, the scoring being made separately for each period, and for each meteorological element of a TAF which

Table II. Characterization of the TAF example from the final score

Scale 0–10	Specific	General
9–10	Excellent	Successful
7–8.9	Very good	
4.6–6.9	Good	
3–4.5	Bad	Unsuccessful
1–2.9	Very bad	
0–0.9	Worst	

includes change groups. All the calculations may be made manually or by using a computer.

The application of the method in the everyday work of a forecasting office will show the advantages, as well as the disadvantages of the method. The disadvantages of the method that will appear during its application will be overcome by some meteorologists who will try to improve on it.

An improvement which would make the method applicable operationally is the creation of a new computer program to enable the method to be used directly from TAFs and METARs; the scoring then being done automatically at the time the TAF expires.

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The spring of 1990 in the United Kingdom

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Summary

Spring 1990 was warm, sunny, and very dry in southern areas but wet in western Scotland. Although May was dry over Scotland, March was the wettest in the Scottish rainfall series beginning in 1869, giving a generally wet spring with more than one and a half times the normal rainfall in all but some eastern areas. Over England and Wales all three months were drier than normal resulting in the driest spring this century. However, there were thundery outbreaks during May with heavy thunderstorms moving across Wales, northern and western England and southern Scotland. It was the sunniest spring over England and Wales since 1948, but dull wet weather over north-western areas in March brought Scotland's sunshine closer to the average.

1. The spring as a whole

Mean temperatures over the spring of 1990 were above average everywhere in the United Kingdom, ranging from 0.5 °C above average in some parts of north-west Scotland to 2 °C above average in the Solent area, the coast of East Anglia, and at places in western Wales and the south-west Midlands. The Central England Temperature of 9.95 °C was the highest spring temperature since 1945 and the second highest this century in the register of Central England Temperatures dating back to 1659. Rainfall amounts over the three months were above average over western and northern parts of Scotland and below average elsewhere, reaching 243% in the area of Fort Augustus, Highland Region, with a contrasting 24% in the south Midlands. Although May was dry over Scotland, March was the wettest in the Scottish rainfall series beginning in 1869, giving a generally wet spring with more than one and a half times the normal rainfall in all but some eastern areas. Over England and Wales all three months were drier than normal resulting in the driest spring since 1893. Spring sunshine amounts were about the average in the Western Isles and above average elsewhere ranging from

97% at Benbecula, Western Isles to 154% at Watnall, Nottinghamshire. With above average sunshine in most places, particularly in south-eastern parts of the United Kingdom, England and Wales had the sunniest spring since 1948; however, a spell of dull wet weather over north-western areas in March brought Scotland's sunshine closer to the average.

Information about the temperature, rainfall and sunshine during the period from March to May 1990 is given in Fig. 1 and Table I.

2. The individual months

March. Mean monthly temperatures were above normal everywhere in the United Kingdom, ranging from just over 1 °C above normal in Shetland to 3.5 °C above normal at Leeming, North Yorkshire. Sheffield (Weston Park), South Yorkshire had the highest mean temperature for March since 1961. Coventry School (Bablake), Warwickshire reported the warmest March this century. Provisional values in the register of Central England Temperatures suggest that it was the warmest March since 1957. Monthly rainfall totals were below normal everywhere except western and northern Scotland and ranged from more than four times the normal at Fort William, Highland Region to as little as 7% of normal at Worthing, West Sussex. At Fort Augustus, March 1990 was the wettest month in the 100-year record; in contrast, provisional figures suggest that over England and Wales as a whole it was the driest March since 1961. Sheffield (Weston Park) had the lowest March rainfall total since 1973. Monthly sunshine amounts were above average in central and eastern areas but below average in western coastal areas from Scilly to Orkney, ranging from more than 150% of average in the east Midlands to less than half the average at Benbecula, Western Isles. Sheffield (Weston Park) had the highest March sunshine total since 1978. Coventry School (Bablake) reported the sunniest March since 1967.

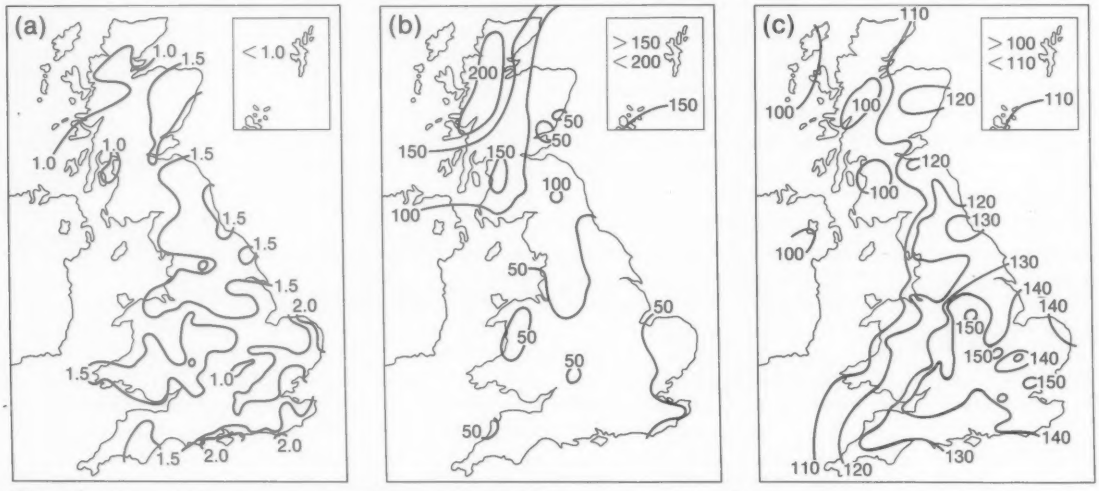


Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for spring, 1990 (March–May) relative to 1951–80 averages.

Table I. District values for the period March–May 1990, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+1.0	+11	166	100
Eastern Scotland	+1.5	−2	81	115
Eastern and north-east England	+1.7	−4	50	132
East Anglia	+1.5	−6	55	143
Midland counties	+1.4	−6	40	136
South-east and central southern England	+1.6	−6	42	141
Western Scotland	+1.1	+2	131	99
North-west England and North Wales	+1.5	−3	60	110
South-west England and South Wales	+1.5	−4	42	120
Northern Ireland	+1.4	0	89	100
Scotland	+1.2	0	139	105
England and Wales	+1.6	−5	48	131

Highest maximum: 28.3 °C in Midland counties in May.
Lowest minimum: −6.8 °C in Northern Ireland in April.

The month was generally wet in western Scotland, but dry and mild in the south and east. Between the 7th and 21st it continued unsettled in Scotland. It was very wet at times in the western Highlands but on most days only small amounts of rain reached coastal fringes to the east of the Grampians and Southern Uplands. England and Wales continued to have a good deal of dry weather, but with short unsettled interludes. Thunderstorms, often accompanied by hail, occurred over north-east England and East Anglia on the 1st, locally in the north-west on the 19th and at Fair Isle, Shetland on the 22nd. On the 25th heavy showers with hail and thunder occurred in south-east England. Scattered hail showers fell in western Scotland on the 2nd, over Scotland and Northern Ireland on the 9th and there were widespread hail showers on the 24th. There were reports of deposits of coloured dust on the 19th at Llanymawddy, North Wales, Northwood, Greater London and Woodley, Berkshire.

April. Mean monthly temperatures were slightly above normal in most areas, although there were a few places with temperatures slightly below normal, ranging from 1.2 °C above normal at Lowestoft, Suffolk to 0.9 °C below normal at Lowtown, Co. Antrim. Severe frosts on the 4th and 5th damaged many plants that were further advanced than normal for early April. On the 30th, Sheffield, (Weston Park) reported the highest April maximum temperature since 1949. Monthly rainfall totals were below normal everywhere except for northern and western Scotland, south-east England and East Anglia, and ranged from 206% at Fort Augustus, Highland Region to as little as 17% at both Hartburn Grange, Cleveland and Leeming, North Yorkshire. The monthly total of 7 mm at Tynemouth, Tyne and Wear is the lowest for April at the station since 1912, when only 3 mm was measured. Monthly sunshine amounts were above average nearly everywhere, apart from a few locations in western Scotland and Northern Ireland, ranging from 179% at Writtle, Essex to 87% at Onich, Highland Region. Aberdeen Airport's sunshine total of 209 hours was the highest there in April since records began in 1946, and Leuchars had 217 hours, the sunniest April since the record began in 1922.

Most places had a dry month, although it was wet over western Scotland and east Kent. Much of the southern and eastern parts of England and Wales and eastern Scotland had one of the sunniest Aprils this century. After a warm start to the month the first week was generally cold, the coldest spell in the first four months of the year. It became warmer, but less settled during the second week. After rain on the 13th the following week was unsettled, cold and windy although with sunny periods. From the 27th it became sunny and warm once more. Thunderstorms were frequent during the second and third weeks, especially between the 13th and 24th, often with heavy showers and sometimes accompanied by hail. Hail showers were frequent during the month, occurring somewhere almost daily during the first three weeks.

May. Mean monthly temperatures were above normal everywhere and ranged from less than 0.5 °C above normal in north-west Scotland to 3 °C above normal in parts of the Midlands. Temperatures exceeded 26 °C somewhere in Great Britain on each of the first five days, giving the hottest start to May this century. Monthly rainfall totals were below normal everywhere except for a narrow band from about Prestwick to Newcastle, where totals were above normal. Much of England and Wales had less than half the normal rainfall and parts of the south Midlands and central and southern England had below 10%. Totals ranged from 146% at Newcastle upon Tyne to 6% at Benson, Oxfordshire and Easthampstead, Berkshire. Monthly sunshine amounts were above or near average everywhere, ranging from 100% at Dyce, Grampian Region to 157% at Rhoose, Mid Glamorgan.

After a hot, dry start a spell of much cooler, showery weather, lasting several days, moved slowly across the United Kingdom from north-west to south-east, though a few places escaped the showers. It became dry again in most places after the 15th, although there was further unsettled weather in many areas towards the end of the month. Isolated thunderstorms developed over western Scotland on the 4th and over southern England and East Anglia on the 6th. Showery outbreaks affected most northern areas on the 8th, sometimes accompanied by thunder; during the evening, thundery showers crossed the English Channel to the Kent coast. Thundery outbreaks occurred on the 9th over northern areas and on the 10th over southern England, spreading later into East Anglia and becoming more widespread during the afternoon, with further thunderstorms developing along the south coast. There were reports of isolated thunderstorms on the 14th and 15th. Hail showers fell over the far north of Scotland on the 24th and a thunderstorm was accompanied by hail over Humberside on the 27th. On the 27th a 20-metre high whirlwind was observed at Towy Castle, South Wales.

Notes and news

European Geophysical Society

This year sees the European Geophysical Society (EGS) celebrate its Twentieth Anniversary. To mark the occasion a special scientific programme of 95 sessions covering solid earth geophysics and marine, atmospheric, planetary and space sciences has been compiled for the 16th General Assembly to be held in Wiesbaden, Germany, 22–26 April 1991. About 2000 scientists from more than 40 different nations are expected to participate.

The 17th General Assembly will be held in Edinburgh, 6–10 April 1992. The meeting is open to all scientists of all nations. Deadline for receipt of abstracts is 15 January 1992. Further details can be obtained from the local organizer:

Prof. K.M. Creer
Dept of Geophysics
James Clerk Maxwell Building
Mayfield Road
Edinburgh EH9 3JZ

Further details on the EGS appeared under Notes and news in the February 1989 edition of *Meteorological Magazine*.

Review

The earth's climate and variability of the sun over recent millennia, edited by J-C. Pecker and S.K. Runcorn. 214 mm × 302 mm, pp. ix+289, *illus*. London, The Royal Society, 1990. Price £40.00. ISBN 0 85403 406 4.

This well-produced volume contains the 28 papers, and associated discussion, presented to the joint Royal Society and Académie des Sciences meeting held in February 1989. This was organized by Jean-Claude Pecker of the College de France and Stanley Keith Runcorn of the University of Newcastle upon Tyne, who have also edited the publication.

The 'trigger' for the meeting was the discovery, as a by-product of using tree rings to improve the calibration of carbon-14 dating, of an approximate 200-year period in the carbon-14 generation rate in the high atmosphere. This is almost certainly attributable to variations in cosmic rays, in their turn influenced by changes in the magnetic activity of the sun. Measurements of beryllium-10 in ice cores have provided additional evidence for this variation in solar activity.

The authors of the papers come from a variety of disciplines (geology, archaeology, astronomy and the environmental sciences) and from as far afield as the USA, China and Australia, as well as Europe. Most of the papers are concerned with carbon-14 and beryllium-10 investigations, but astronomical and observational aspects of solar variation, the possible relationships between climate and solar activity, and the study of the sun itself, are also covered. The papers appear to be 'state of the art' and are accompanied by copious up-to-date references. There is, however, no index.

The 11-year sunspot cycle is, of course, well documented, but attempts to find corresponding variations in the earth's climate have so far proved inconclusive. However, the 11-year variation has itself shown cyclic behaviour with a period of about 200 years. For example, the era of weak sunspot activity from about AD 1645–1715 (the so-called Maunder Minimum), at around the time of the Little Ice Age, was preceded by other minima at approximately 200-year intervals back to the end of the first millennium AD. H.H. Lamb's discovery that these minima correlated with cold winters in western Europe aroused much interest but, of course, evidence extending over less than 1000 years is insufficient to establish a 200-year cycle. Support for the existence of the 200-year cycle for possibly the last 2000 years is, however, found in the Chinese sunspot record.

The significance of the findings presented in this volume is that the examination of tree rings and ice cores enables the period over which solar variation can be studied, albeit by proxy, to be measured in thousands rather than hundreds of years.

Does this work have any relevance for meteorologists? To quote from S.K. Runcorn's closing remarks: 'The greenhouse effect points to the need for a better understanding of the atmosphere and of climatic change. By studying the effect of the changes of solar output with periods of 11 and 200 years on the atmosphere from the historic and archaeological records, we may hope to come to a better understanding of the earth's atmosphere and how it responds to changing energy input. In geophysics we have to wait for nature to do the experiment. But in assessing the influence of the greenhouse effect from observations over the past 150 years, the possibility that some of the change may be due to the 200-year cycle in the sun must be considered. We showed in the introductory remarks that the global increase in temperature over the second half of the last century and the first half of this correlates with the sun's activity, as determined by geomagnetic disturbances. This implies that at least some part of the observed increase in temperature is due to increased solar energy output'. Conversely, if the 200-year cycle places us in a solar minimum in the first half of the next century, might this not mitigate the greenhouse warming, at least to some extent.

In the preface to their book, the editors express the 'hope that this important interdisciplinary subject will attract young and enthusiastic workers'. Its publication should go a long way towards fulfilling that hope.

P.M. Stephenson

Satellite photographs — 24 October 1990 at 1242 UTC

The main feature on the AVHRR infra-red (IR) image of the central Mediterranean (Fig. 1) is the spectacular plume of cold cloud-tops extending over 500 km eastwards from an apparent generation point just south-west of Malta (M). The plume is associated with thunderstorms whose anvils have merged, and is a prime example of the distinctive patterns Mesoscale Convective Systems (MCSs) can display on IR images. Although little detail can be made out within the body of the plume, there are marked variations in cloud-top temperature gradient around the periphery. Note the very steep gradient at A and B compared with the much more gradual changes at C and D. Juying and Scofield* have shown that within an MCS cloud-shield, regions of steep cloud-top temperature gradient correlate closely with the heaviest precipitation.

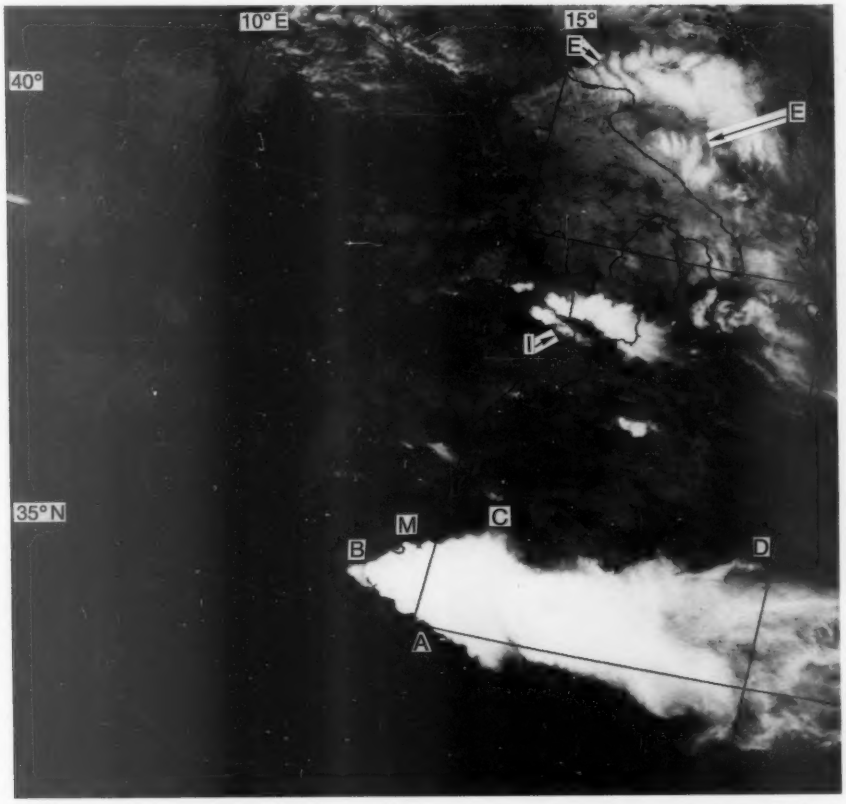
The corresponding visible image in Fig. 2 provides additional detail on cloud structure within this system. Notice in particular the bright lumpy texture to the cloud tops — implying active convection — in the western portion (W) where a marked shadow (S) is being cast on much lower cloud, also in the more central portion of the cloud shield and along the spine. Much of the eastern portion is relatively thin cirrus.

The water vapour image from Meteosat (Fig. 3) shows that the MCS developed where dry mid-tropospheric air with relatively low wet-bulb potential temperature (θ_w) began to overrun a tongue of moist higher θ_w air at low levels (Fig. 3). A weak surface trough extended from Libya to Sicily and dew-points as high as 21 °C were reported in the Malta area. The plume formed in the region of marked vertical wind-shear with anvil cirrus carried eastwards in the strong westerly upper flow — 70 kn at 300 mb over Sicily (Fig. 4).

Other features of interest on both images include areas of deep convection over southern Italy (I on Fig. 1) and marked waves in the upper cloud over the Adriatic (E on Fig. 1). These may be gravity waves resulting from deep convection being 'damped' at the tropopause.

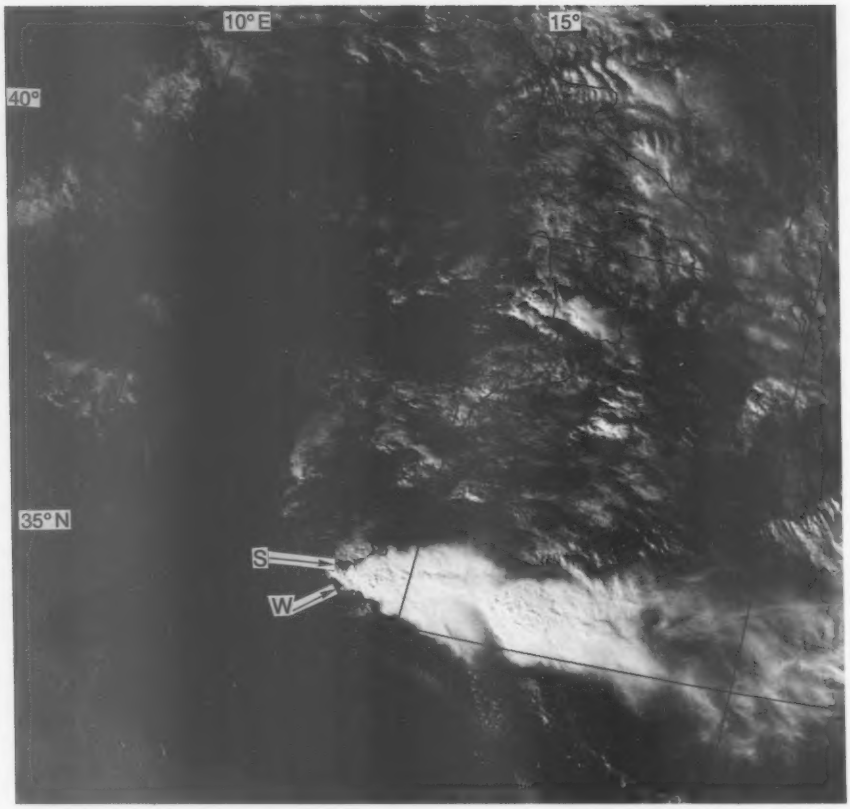
A.J. Waters and D. Ratcliff

* Juying, X. and Scofield, R.A.; Satellite-derived rainfall estimates and propagation characteristics associated with mesoscale convective systems (MCSs). Washington DC, NOAA, Technical Memorandum NESDIS 25, 1989.



Photograph by courtesy of University of Dundee

Figure 1. NOAA-11 AVHRR infra-red image at 1242 UTC on 24 October 1990. The labels refer to features mentioned in the text.



Photograph by courtesy of University of Dundee

Figure 2. As Fig. 1 but visible image.

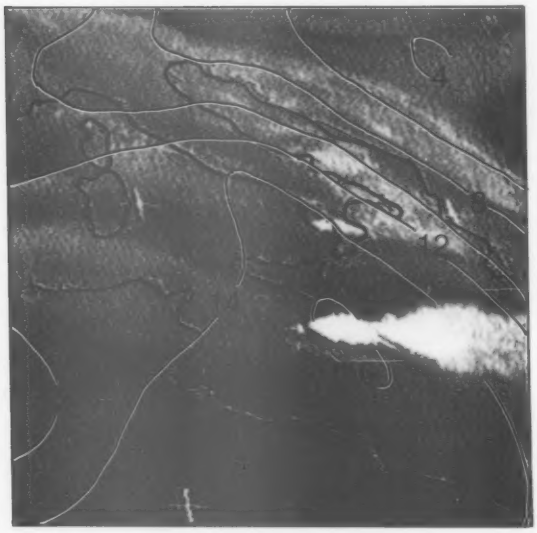


Figure 3. Meteosat water-vapour image at 1130 UTC on 24 October 1990. Black indicates dry mid-tropospheric air, higher moisture content being shown by progressively lighter shades of grey and the continuous lines indicate wet-bulb potential temperature (°C).

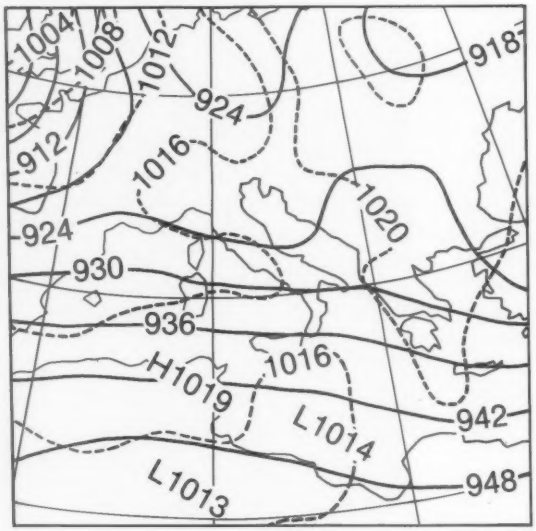


Figure 4. Contours of the 300 mb surface (dam) (continuous lines) at 1200 UTC on 24 October 1990 with mean-sea-level isobars (mb) superimposed as dashed lines.

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Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (Compucorp or IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

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